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TURBULENT FLOW OF DRAG-REDUCING SUSPENSIONS

by

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13. ABSTRACT

The friction-reducing properties of fiber suspensions were investigated. Fibers of asbestos, glass, and acrylic were found to greatly reduce the turbulent-flow resistance of both aqueous and non-aqueous suspending fluids. Pipe-flow and rotating-disk experiments show that fibers having the smallest diameter, and substantial length-to-diameter ratio gave the most friction reduction at the smallest weight concentration of fiber. An asbestos fiber gave 65 percent friction reduction in a small pipe-flow apparatus and 48 percent in the rotating-disk equipment (both being the maximum obtainable in the devices) at a suspension concentration of 500 ppm.

Details of illustrations in
this document may be better
studied on microfiche

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SUMMARY

PROBLEM

Investigate the friction-reducing properties of fiber suspensions (a) from the stand-point of possible Navy utilization of the effect in deep-operating flooded motors, and other applications such as oil pipelines, and also (b) as a possible model, on an enormously increased scale, of the action of friction-reducing polymer molecules in solution.

RESULTS

Fibers of asbestos, glass, and acrylic were found to greatly reduce the turbulent-flow resistance of both aqueous and non-aqueous suspending fluids. Pipe-flow and rotating-disk experiments show that fibers having the smallest diameter, and substantial length-to-diameter ratio gave the most friction reduction at the smallest weight concentration of fiber. An asbestos fiber gave 65 percent friction reduction in a small pipe-flow apparatus and 48 percent in the rotating-disk equipment (both being the maxima obtainable in the devices) at a suspension concentration of 500 ppm.

RECOMMENDATIONS

Continue the study of drag-reducing fibers in order to provide data for possible Navy applications, and to increase understanding of the mode of action of friction-reducing materials in solution and suspension.

CONTENTS

INTRODUCTION

The turbulent flow of solutions of dissolved macromolecules that have lower friction drag than the solvent alone has received intensive study in recent years (Ref. 1). Fluids containing solid particles in suspension have been studied over a much longer period of time than has polymer solution flow, but less intensively. Consequently, the overall understanding of the effects of small amounts of solid material in the suspending liquid appears to be less well developed than is the case with polymer solutions. Yet the drag-reduction effects found in turbulent flow of suspensions are just as remarkable, if not more so, than those found in polymer solutions.

BACKGROUND

A number of early observations of natural phenomena, together with laboratory studies of simulated natural flow situations and the systematic study of suspensions flowing in pipes, form the background for the present study of suspension flow. McMath (Ref. 2), on the basis of observations of the Mississippi River, noted in the 1880's that turbid streams flow faster at a given stage than clear streams. This contradicts the intuitive idea that the addition of suspended material would tend to decrease flow due to a higher resistance and because of the energy required to carry the material in suspension.

McMath's observations were not confirmed until 1921, when Buckley (Ref. 3) made a detailed study of stream flow rates and velocities on the river Nile during periods of rising and falling flood stages. His data show greatest flow rate and velocity at a given river elevation when the sediment concentration is highest. Thus the effect of the suspended sediment on the river caused the flow rates and velocities to be much higher on the rising flood stage compared with the falling.

The first really comprehensive laboratory experiments concerning the effect of suspended materials on the frictional coefficient of flowing water were made by Vanoni (Ref. 4) at the California Institute of Technology. His experiments were made with water containing various amounts of sand in suspension and flowing in a small flume. The test results, which were later repeated and extended (Ref. 5), showed that frictional reductions as high as 28 percent were obtained when water containing sand in suspension was used in the flume. The literature shows that measurements of the pipe flow of water suspensions of sand (Ref. 6), emery (Ref. 7), polystyrene spheres (Refs. 8, 9), clay, lime, and cement (Ref. 10), thorium oxide (Refs. 11, 12), and charcoal, flyash, and coal (Ref. 13) occasionally indicate lower frictional resistance in turbulent flow than does clear water.

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VERY EFFECTIVE DRAG-REDUCING SUSPENSIONS

In 1958, Daily and Bugliarello (Ref. 14) began pipe-flow studies of wood pulp suspended in water. Their results showed that even though the frictional coefficient in laminar flow was substantially greater than that of pure water, the turbulent flow of the suspensions had a greatly reduced friction coefficient. In fact, the friction was reduced as much as 40 percent for a 1-percent solution of ground poplar wood flowing in a 2-in. pipe. Daily and Bugliarello also found that the turbulent fluctuations were less intense when the wood pulp suspensions were present in the flow.

The turbulent flow of a suspension of nylon fibers in water was studied by Bobkowicz and Gauvin (Ref. 15). They found friction reductions of over 50 percent in 1-in. pipe using nylon fibers approximately 1 mm in diameter and about 50 mm long. The higher the concentration (up to 4 percent), the greater the friction reduction. In a later study (Ref. 16), Bobkowicz and Gauvin noticed that while the turbulence intensity in a longitudinal direction was decreased, there seemed to be a simultaneous increase in the radial direction. Mih and Parker (Ref. 17) also found a suspension of rayon fibers, 17 μ in diameter, with length-to-diameter ratio of 380, to be strongly friction-reducing in both 2-in.- and 4-in.-diameter pipes.

The flow of asbestos slurries in seawater was studied by Lummas and Randall (Ref. 18), who found a 16-percent friction reduction, compared with seawater, initially after mixing. After a long period of circulation in the experimental pipe-flow rig, the friction reduction improved to 26 percent. This improvement with shear is consistent with the finding that mineral (chrysotile) asbestos exists as a bundle of microscopic fibrils, which can be dispersed by intensive shear to give a loose fibril structure. Arranaga (Ref. 19) has shown that large friction reduction can be obtained from asbestos slurries when the fibril bundles are dispersed by means of intensive shear. Friction reductions attainable with asbestos fiber slurries were shown to be comparable to those with polymer solutions.

Using asbestos fibrils especially processed to preserve a very high length-to-diameter ratio, Ellis (Ref. 20) found drag reduction to occur at suspension concentrations as low as 10 ppm. Values of friction reduction as high as 44 percent were found for 100 ppm in a 1.43-cm tube. The length-to-diameter ratio for these very fine fibers (Ref. 21) was believed to be on the order of 10^5. These experiments are of major significance, since the drag reductions obtained are comparable, on a weight basis, to those obtained with very good polymer solutions. Suspension technique is critical, however. VanDriest (Ref. 22) was unable to show friction reduction with his asbestos-water mixture.

As an addendum to this discussion, it should be noted that Sproull (Ref. 23) and especially Boyce and Blick (Ref. 24) have shown that dusty air has a considerably lower frictional coefficient than clear air. Saffman (Refs. 25, 26) has suggested that coarse dust particles provide a damping effect, which can stabilize an otherwise unstable laminar flow of gas.

In summary, the unexpected result that the addition of a dust or sediment or fiber to the turbulent flow of a fluid can lead to frictional coefficients lower than those of the

pure fluid seems to be verified by a large number of experimenters. When the added substance has a relatively high length-to-diameter ratio, friction reductions of 50 percent or more can be achieved. The understanding and eventual application of this important effect and its relationship to the mechanism of friction reduction in high polymer solutions is the topic of current research.

VISCOSITY

Theoretical and experimental studies indicate the viscosity (a laminar-flow measurement) of a suspension is greater than the suspending fluid. The fundamental viscosity relationship for suspensions of spherical particles is due to A. Einstein (1906), who derived an expression for the relative viscosity

$$\eta/\eta_0 = 1 + 2.5\phi,$$

where

$$\eta = \text{viscosity of suspension}$$
$$\eta_0 = \text{viscosity of suspending fluid}$$
$$\phi = \text{volume ratio of spheres to fluid}$$

The theory assumes the spheres are far enough apart so that there are no interactions between them. For volume ratios less than about 2 percent, the Einstein equation is in excellent agreement with experimental results.

For volume ratios up to about 10 percent, Cheng and Schachman (Ref. 27) suggest:

$$\eta/\eta_0 = 1 + 2.5\phi + 10\phi^2 + 50\phi^3,$$

which fits their experimental data very precisely.

For suspensions of sharp-edged particles, such as emery, the results of Maude and Whitmore (Ref. 7) may be applicable. Their data can be fitted with a modified Einstein equation to give

$$\eta/\eta_0 = 1 + 10\phi + 10\phi^2$$

as an approximation for the relative viscosity.

The viscosity of suspensions of flexible, fiber-like particles is not well defined. According to the results of Nawab and Mason (Ref. 28) the viscosity of 3.5-μ-diameter rayon fibers depends on the axial ratio and the stiffness. At axial ratios less than about 100, the particles are rigid and have a viscosity close to that predicted by Jeffery (Ref. 29). Longer particles of moderate flexibility seem to increase in viscosity with axial ratio, but at a rate much less steep than that of extremely long, flexible fibers.

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In every case, the addition of particles to a fluid is seen to increase the viscosity and, thus—if the fluid behaved in a Newtonian way—to increase both laminar and turbulent friction.

VISCOELASTIC EFFECTS

Nawab and Mason (Ref. 28) found a strong Weissenberg effect (i.e., fluid climbing a rotating stirring rod) in their suspension of 3.5-μ-diameter rayon fibers for all axial ratios of fiber greater than 175. This suggests that the fibers do not remain rigid, but undergo viscoelastic bending when sheared. Bugliarello and Daily (Ref. 30) found viscoelastic behavior in wood-pulp suspensions. Suspensions of Kraft pulp, set in rotation in a cylindrical container, were measured for angular motion when the container was brought to a stop. The suspensions would rotate backwards, in a direction opposite to the original rotation, before coming to rest. This counter-rotation is a measure of viscoelastic behavior. Since elastic elements are required in the fluid to provide these effects, it is evident that the fibers play a large role in changing the structure of the fluid response. Attanasio et al. (Ref. 31) found viscoelastic behavior in wood-pulp suspensions of concentrations of 1 percent and below; the viscoelasticity varied with fiber length and type as well as concentration.

EXPERIMENTAL

Three types of friction-measuring devices were employed in the study reported herein. Most data were obtained using a 5-in.-diameter disk rotating in 14,000 ml of water or suspension. Where quantities of test material were limited, a 3-in. disk rotating in 1,000 ml of water or suspension was employed. The maximum Reynolds numbers achievable, based upon tip radius, were 10^6 for the 5-in. disk and 0.5×10^6 for the 3-in. disk.

In each case the disk was driven by a Cole-Parmer Model 4425 dynamometer, with electronic speed control and integral torque meter, the output of which was read on expanded scales of an electronic voltmeter. Prior to use, the torque meter was calibrated by a small Prony brake. Speed was read on the dynamometer tachometer, and the scale calibrated by a precision strobotachometer. Temperatures of the suspensions were monitored by a calibrated glass thermometer reading in tenths of a degree centigrade. The general arrangement of the disk apparatus is shown in Fig. 1.

The third method of friction measurement was the turbulent-flow rheometer (Ref. 32). This is, in essence, a small pipe-flow apparatus which allows the measurement of the friction in a length of 0.046-in.-diameter tubing at a constant Reynolds number of 14,000. This was used for suspensions of up to 2 percent or so by weight; higher weight suspensions caused blockage of the instrument.

No special care was used in preparing the suspensions (other than accurate weighing), except for the important point of utilizing a surfactant solution for dispersing the various kinds of asbestos. This noteworthy addition to the technique is attributable to Ellis
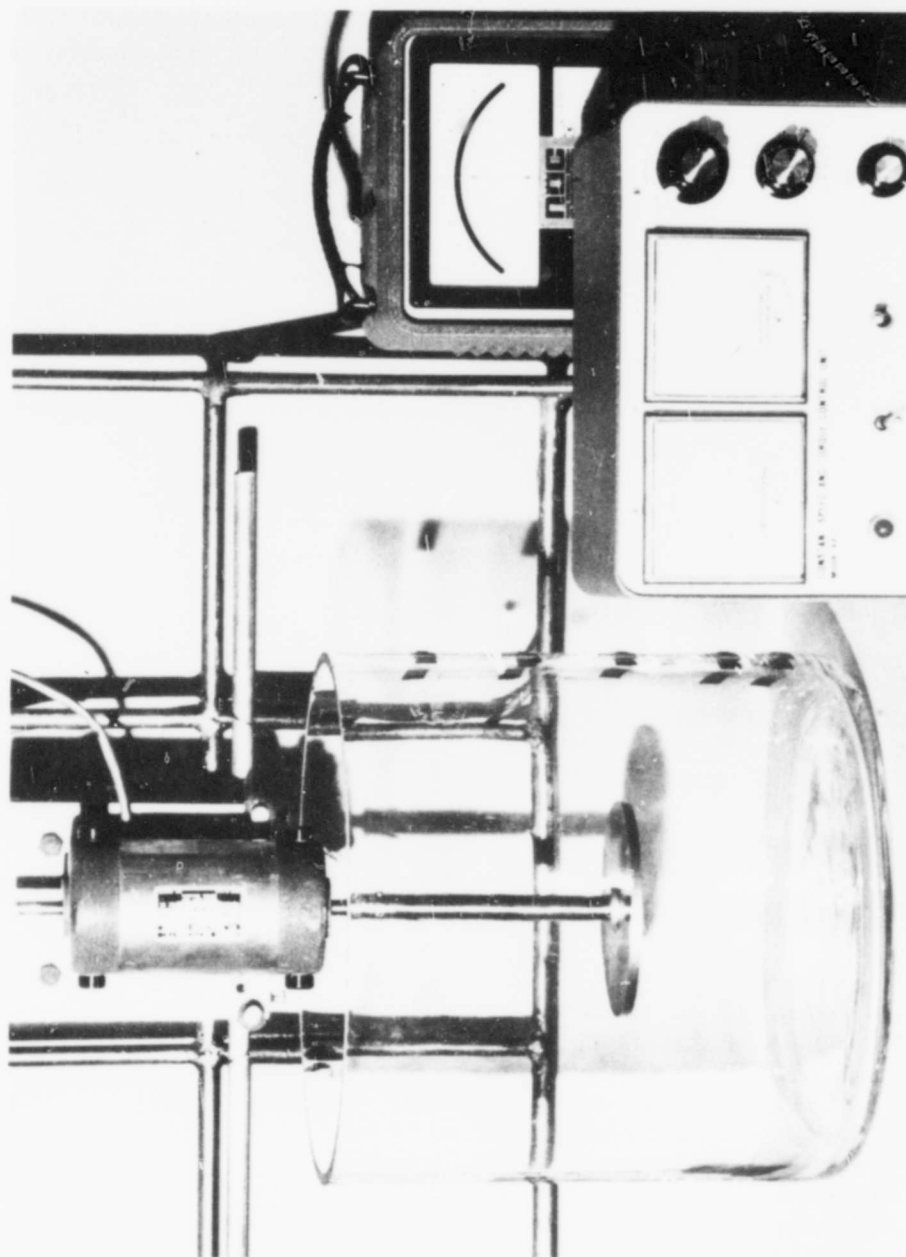
Figure 1. View of rotating-disk friction-measuring apparatus.

(Ref. 20) and Atkinson et al. (Ref. 21) and was invaluable in obtaining rapid dispersion of the asbestos and achieving high values of friction reduction. For the asbestos fibers, then, an 0.8-percent solution by weight of the surfactant Aerosol OT was used instead of pure water. This material had no effect on the friction as measured by the rotating disks or the turbulent-flow rheometer.

The following fibers were used in the study:

Asbestos	Manufacturer
Turner Suspension	Turner Bros. Asbestos, Ltd.
7K05	Johns-Manville
7-T	Special Asbestos
7-M	Special Asbestos
5R-10	Special Asbestos
M-8	Special Asbestos
MS-7	Special Asbestos
HPO	Union Carbide
R-G 144	Union Carbide
Avibest C	FMC Corporation
"Long Fiber"	General Chemical Company

Other	Manufacturer
701 glass fibers	Thalco
Chopped glass fibers	(unknown)
Rayon fibers	S. L. Abbot Company
Solka-Floc	Brown Company
Benaqua	National Lead Company
847 glass fibers	Thalco
Treated glass fibers	Prof. A. B. Metzner
Acrylic fibers	Dow Badische

In order to compare the observed friction-altering ability of the fibers with their general structure, samples of each material were taken from the test suspension for examination at magnification of 304X. For the asbestos fibers, it was found that use of reflected dark-field illumination gave the best results, and most of the photographs were taken in that way, using a Zeiss Ultraphot III and Type 52 Polaroid film.

Additionally, the fraction of suspended solids (by volume) was determined by allowing a calibrated beaker of material to settle for a period of several days to a week, then observing and photographing the settled fraction.

During the study of the friction-reducing properties of the glass fibers, it became apparent that in water suspensions the fibers would mat together and form a floc, which reduced the effective amount of material in suspension and caused erratic friction readings. In order to study the effect of a different suspending fluid on the friction-reducing properties of glass fibers, a special suspending fluid was developed. This fluid was composed of 40 percent propylene glycol and 60 percent ethyl alcohol and had the property of producing a good, well-dispersed suspension. Additionally, the viscosity was essentially that of water, and there were no hazards or safety problems with its use.

RESULTS

Both the rotating-disk and the turbulent-flow-rheometer technique proved to be excellent methods of acquiring data on the friction properties of drag-reducing suspensions. The disks were especially useful for concentrated suspensions. The rheometer was appropriate for dilute suspensions since these results could be compared with those for polymer solutions (Ref. 33).

VERY EFFECTIVE ASBESTOS DISPERSIONS

The most effective fiber tested in terms of drag reduction was the Turner Brothers asbestos. Figure 2a shows a plot of moment coefficient against Reynolds number for the 5-in. disk with water and with various concentrations of Turner asbestos in suspension. As shown in Fig. 2a, 100 ppm of this material produces a noticeable change in moment coefficient, while 400 to 500 ppm can reduce the moment coefficient by approximately 48 percent. The test data for water alone in this apparatus are in good agreement with the Goldstein equation for the turbulent resistance of a rotating disk and thus show that the suspension results can be relied on to give a good indication of overall drag reduction. Test results with the Turner asbestos suspension in the 3-in.-disk apparatus are shown in Fig. 2b. Here it is to be noted that due to the very high turbulence level in the small quantity of fluid (1,000 ml), higher moment-coefficients have been recorded compared with those shown for the 5-in. disk. Nevertheless, Fig. 3 shows that the results at a given Reynolds number in terms of drag reduction as a function of concentration are almost identical for the 3-in. and 5-in. disks, so that the drag results from the 3-in. disk can be compared with those of the larger apparatus. The maximum drag reduction with each of the disk test rigs at a given Reynolds number is identical with the maximum obtained with polymer solutions at the same Reynolds number (Ref. 34).

The results of testing the Turner asbestos suspension in the turbulent flow rheometer are given in Fig. 4a, while Figs. 4b through 4e present test data from less effective asbestos fibers under the same condition in the turbulent flow rheometer. The Turner material is at least 5 times more effective on a weight basis than the next material tested, which in turn was substantially more effective than the next, and so on. However, the asbestos materials were all extremely good in overall drag reduction. The order of effectiveness from all tests was:
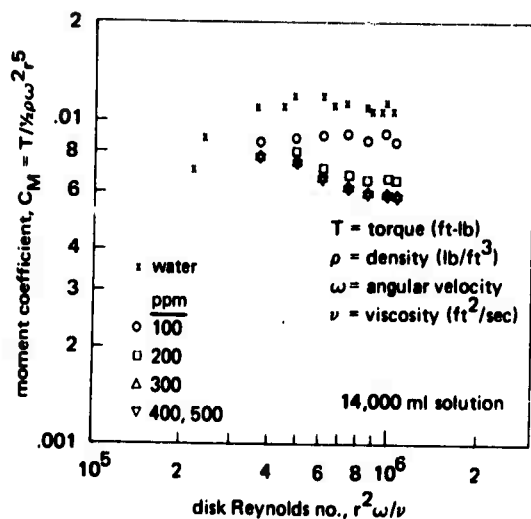
Figure 2a. Moment coefficient as a function of disk Reynolds number for water and Turner asbestos suspensions using the 5-in.-disk apparatus.
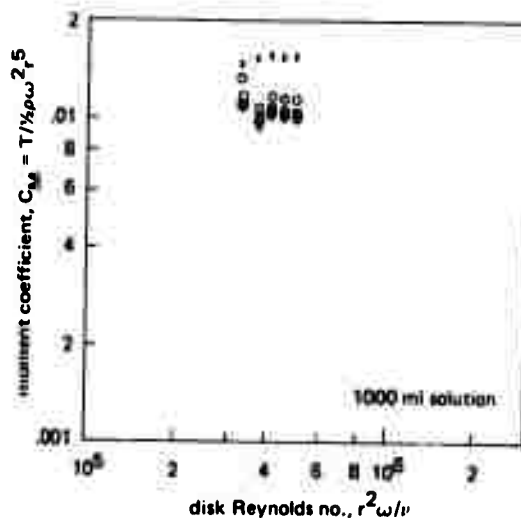
Figure 2b. Moment coefficient as a function of disk Reynolds number for the 3-in.-disk apparatus using water and Turner asbestos suspensions.
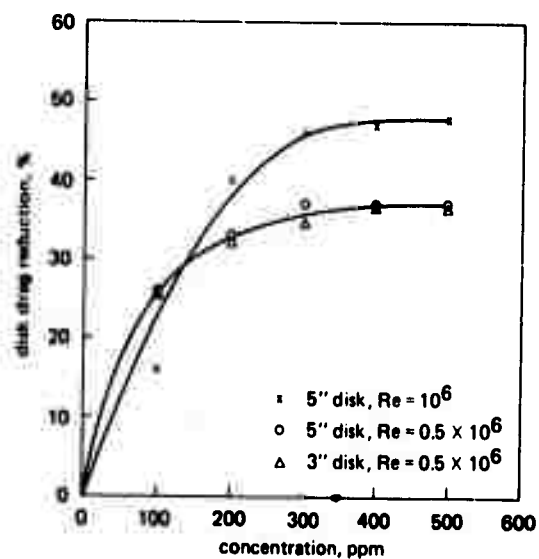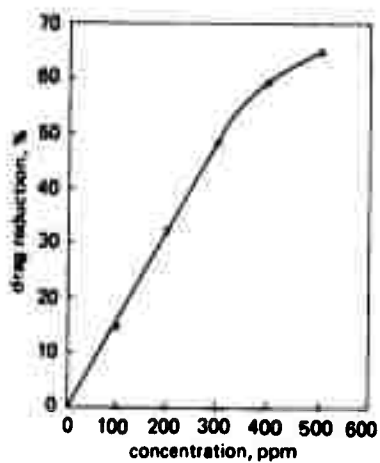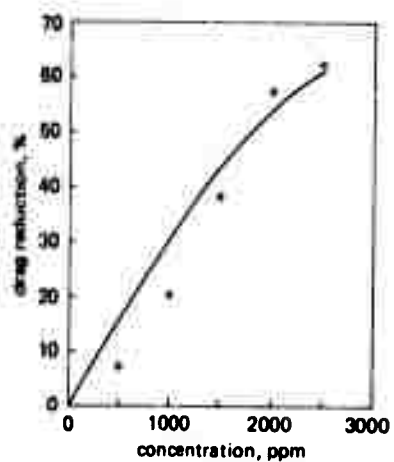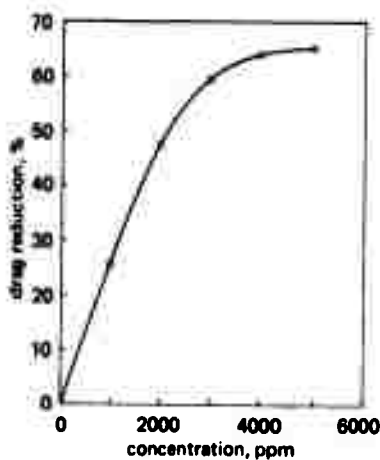

Figure 3. Comparison of disk drag reduction as a function of concentration for Turner asbestos in the two rotating disk devices.
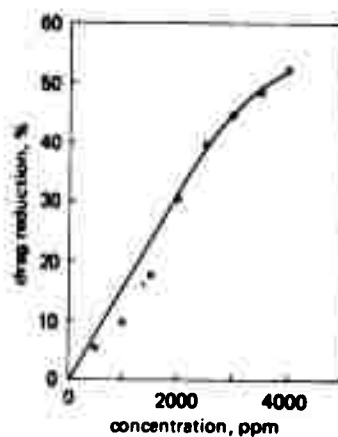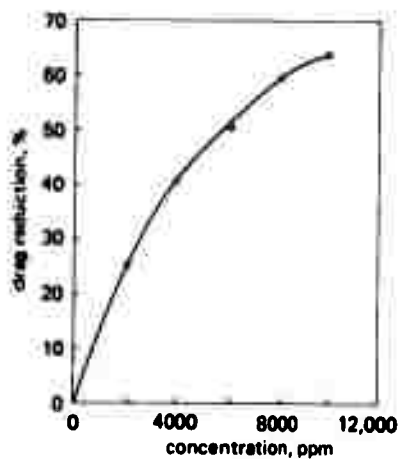
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a. Turner Bros.

b. Special Asbestos Company 5R-10

c. Johns-Manville 7K05

d. Special Asbestos Company 7-M

e. Special Asbestos Company 7-T

Figure 4. Drag reduction-concentration plots for very effective asbestos suspensions in the turbulent-flow rheometer.

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1. Turner Asbestos
2. Special Asbestos Co., 5R-10
3. Johns-Manville 7K05
4. Special Asbestos 7-M
5. Special Asbestos 7-T

Photomicrographs of these suspensions show that the most effective materials are extremely long, hair-like fibers, which seem to become more coarse and less entangled as the drag-reduction effectiveness is diminished. Photomicrographs taken at 304X of the five most effective suspensions are shown in Figs. 5a through 5e. These photographs should be viewed as a general indication of the situation for each dispersion, bearing in mind that Atkinson (Ref. 21) has shown that the fibers exist in sizes too small to be seen by light microscopes, i.e., electron microscopy is required to obtain complete detail of the full range of fiber sizes present in such a dispersion. However, these photographs taken at 304X show an interesting gradation of fibril bundle size and entanglement with degree of drag-reduction effectiveness.

LESS EFFECTIVE ASBESTOS DISPERSIONS

A second group of asbestos suspensions, having a smaller amount of drag-reduction effectiveness, is listed below:

1. Avibest C
2. Union Carbide R-G 144
3. Union Carbide HPO
4. "Long Fiber"
5. MS-7, Special Asbestos
6. M-8, Special Asbestos

The data for suspensions containing these materials are shown in Figs. 6 and 7, where it can be seen that the concentrations required for drag-reduction effectiveness with these materials are measured in percent rather than parts per million. For example, peak drag-reduction effectiveness of the HPO asbestos in the rotating-disk apparatus (Fig. 7) was achieved with about 2-percent concentration, and for the other materials even higher concentrations were required. Photomicrographs of these materials are given in Figs. 8a through 8f, where it can be seen that the predominant characteristic of this type of material is the tendency to depart from the long, hair-like appearance of the previous group and take the form of rather rigid, almost needle-like crystals having little apparent flexibility.

OTHER FIBERS

A selection of other fiber substances, including glass of various sizes, diameters, and surface preparations, acrylic fibers, and a prepared wood derivative were tested for friction reduction. These results are presented in Figs. 7, 9, 10, and 11. They indicate that substantial drag reductions, on the order of 10 percent or more, are easily obtainable with a variety
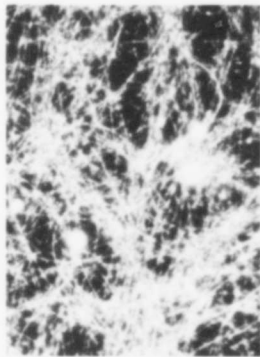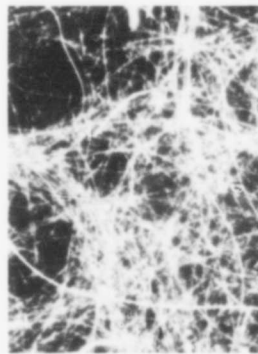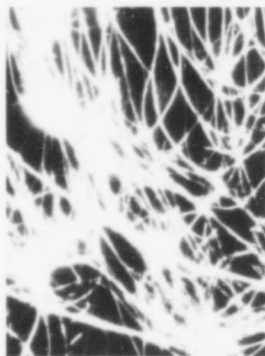
a. Turner Bros.
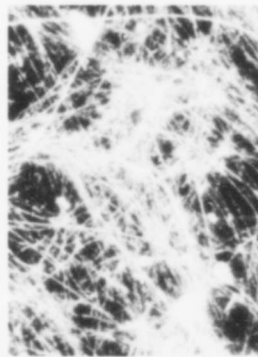
b. 5R-10
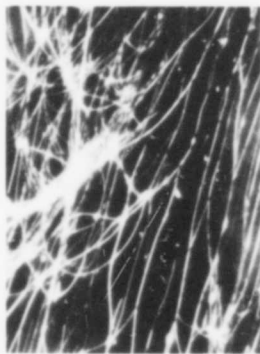
c. 7K05

d. 7-M

e. 7-T

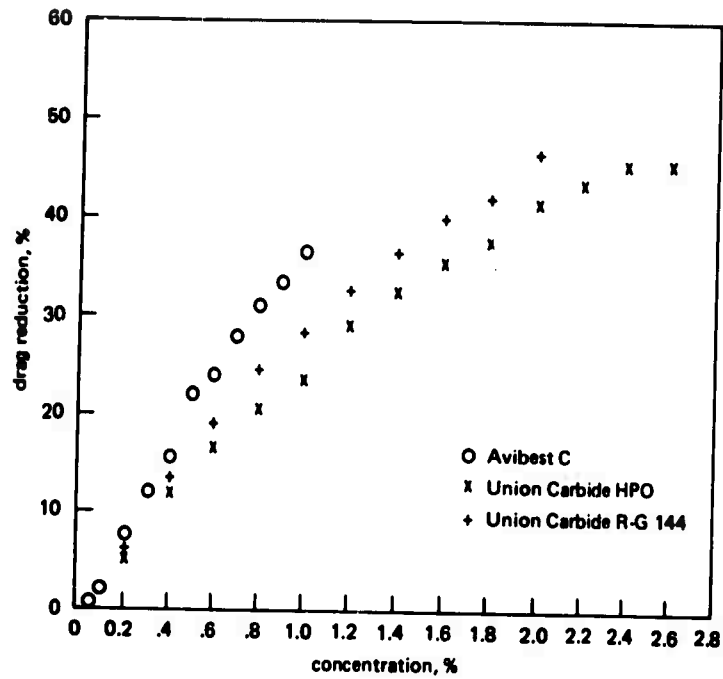Figure 5. Photomicrographs at 304 X of asbestos fibers.

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Figure 6. Drag reduction as a function of concentration for less effective asbestos suspensions in the turbulent-flow rheometer.
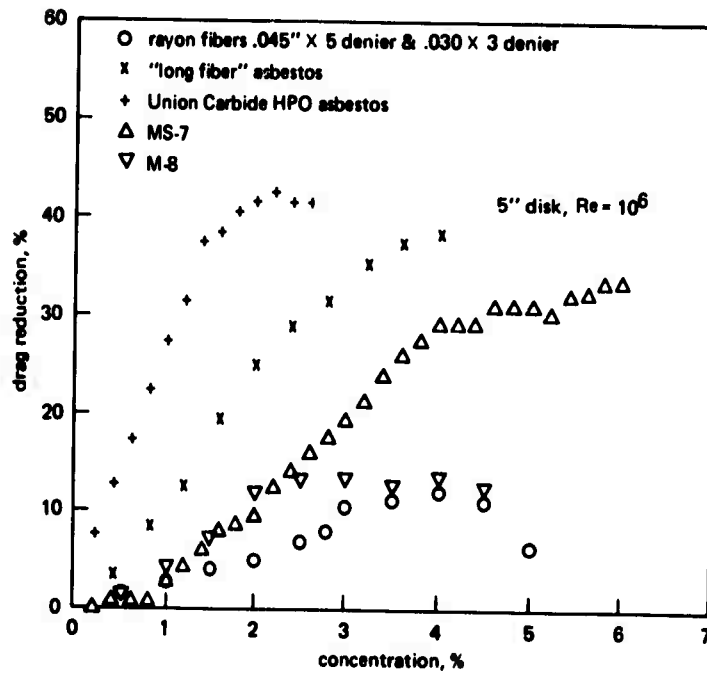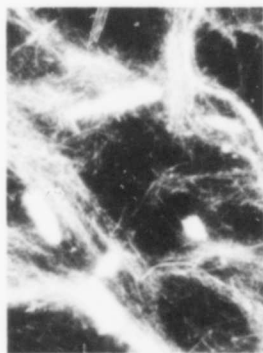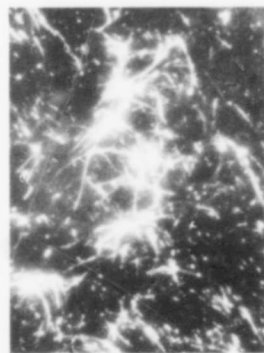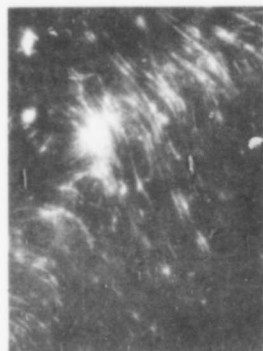

Figure 7. Drag reduction as a function of concentration for asbestos and rayon fibers in the 5-in.-disk apparatus.

a. Avibest C

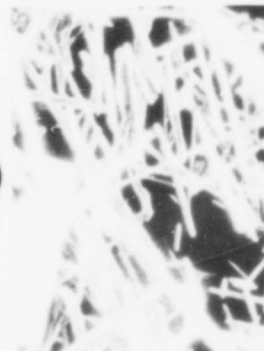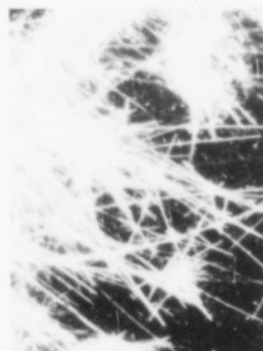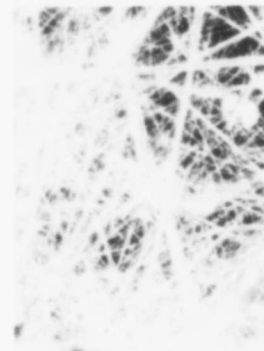b. Union Carbide R-G 144

c. Union Carbide HPO

d. "Long-Fiber"

e. MS-7

f. M-8

Figure 8. Photomicrographs at 304X of less effective asbestos suspensions.
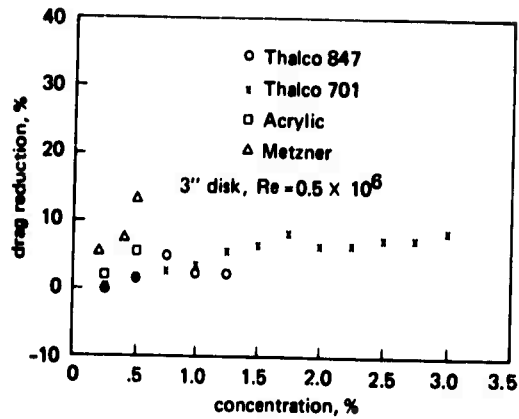
Figure 9. Drag reduction as a function of concentration for fibers in a suspending fluid composed of 40% propylene glycol and 60% ethyl alcohol in the 3-in.-disk apparatus.
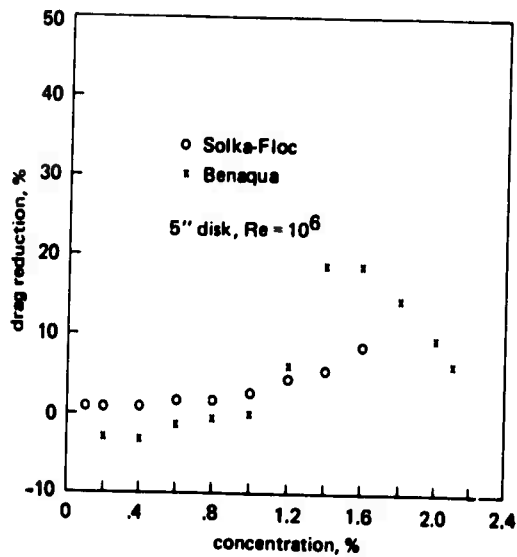

Figure 10. Drag reduction as a function of concentration for a wood fiber and a clay suspension in the 5-in.-disk apparatus using water.
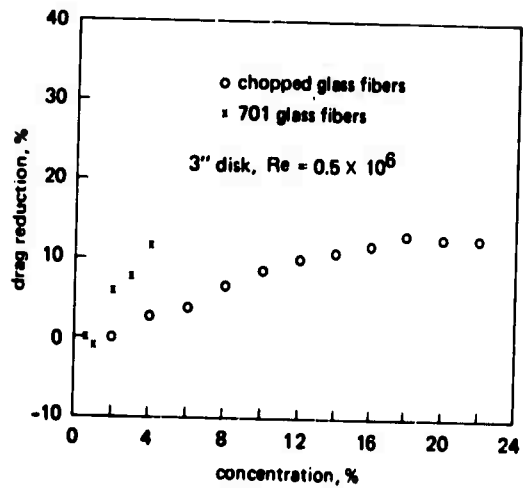

Figure 11. Drag reduction as a function of concentration for glass fibers in the 3-in.-disk apparatus.

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of fibrous substances. The concentrations required varied enormously, depending on the type of fiber, its surface preparation, and perhaps even the suspending fluid. For example, the most effective glass fiber, having a diameter of 0.00037 in. and a length of 1/8 in., treated by Prof. A. B. Metzner at the University of Delaware to remove any surface preparation, gave a friction reduction of approximately 13 percent at a concentration of 0.5 percent. By contrast, however, a commercial sample of chopped glass fibers also gave a 13-percent drag reduction but at a required concentration of 18 percent. The fibers may be listed in the order of effectiveness as follows:

1. Metzner Glass
2. Acrylic Fibers
3. 701 Glass
4. 847 Glass
5. Solka-Floc
6. Rayon Fibers of 0.45 by 5 denier and
   0.30 by 3 denier
7. Chopped Glass

The long fibers seem to perform best in a non-aqueous suspending fluid, as shown in Fig. 9.

The appearance of the fibers under the microscope at 304X is shown in Figs. 12a through 12h. In general, it can be noted that the more effective fibers are, as in the case of asbestos dispersion, of generally long, hair-like appearance. In fact, drag-reduction effectiveness seems to increase almost directly in proportion to length of fibers present. For example, the chopped glass fibers (Fig. 12h) have a very low length-to-diameter ratio and required a high concentration to produce drag reduction.

The effect seems to be partially related to the volume percent of solids in suspension. For example, Figs. 13a and 13b compare the appearance of a settled suspension of 1.6 percent of Solka-Floc having a drag reduction of about 8 percent with a 1.8-percent suspension of chopped glass, which did not reduce the drag at all. In the first case, the volume of solids was about 35 percent of the total volume measured, in the second only 4 percent. Increasing the volume of chopped glass to approximately 22 percent (Fig. 13c) increased the observed drag reduction to approximately 12 percent. Thus, it is apparent that in addition to an effect attributable to concentration by weight, in fiber suspension there is also a volume requirement.

OTHER MATERIALS

Figure 10 presents test results for a suspension of Benaqua, a bentonite clay suspension. This material is believed to exist in the form of small platelets (Ref. 35). As shown in Fig. 10, a substantial drag reduction was achieved with this clay suspension, but in this case it is believed the effect is due to a reduction in the power law exponent, n' [in the notation of Metzner and Reed (Ref. 10)] Metzner and Reed also showed a reduced drag in clay suspensions (compared to water). However, this drag reduction is amenable to analysis by
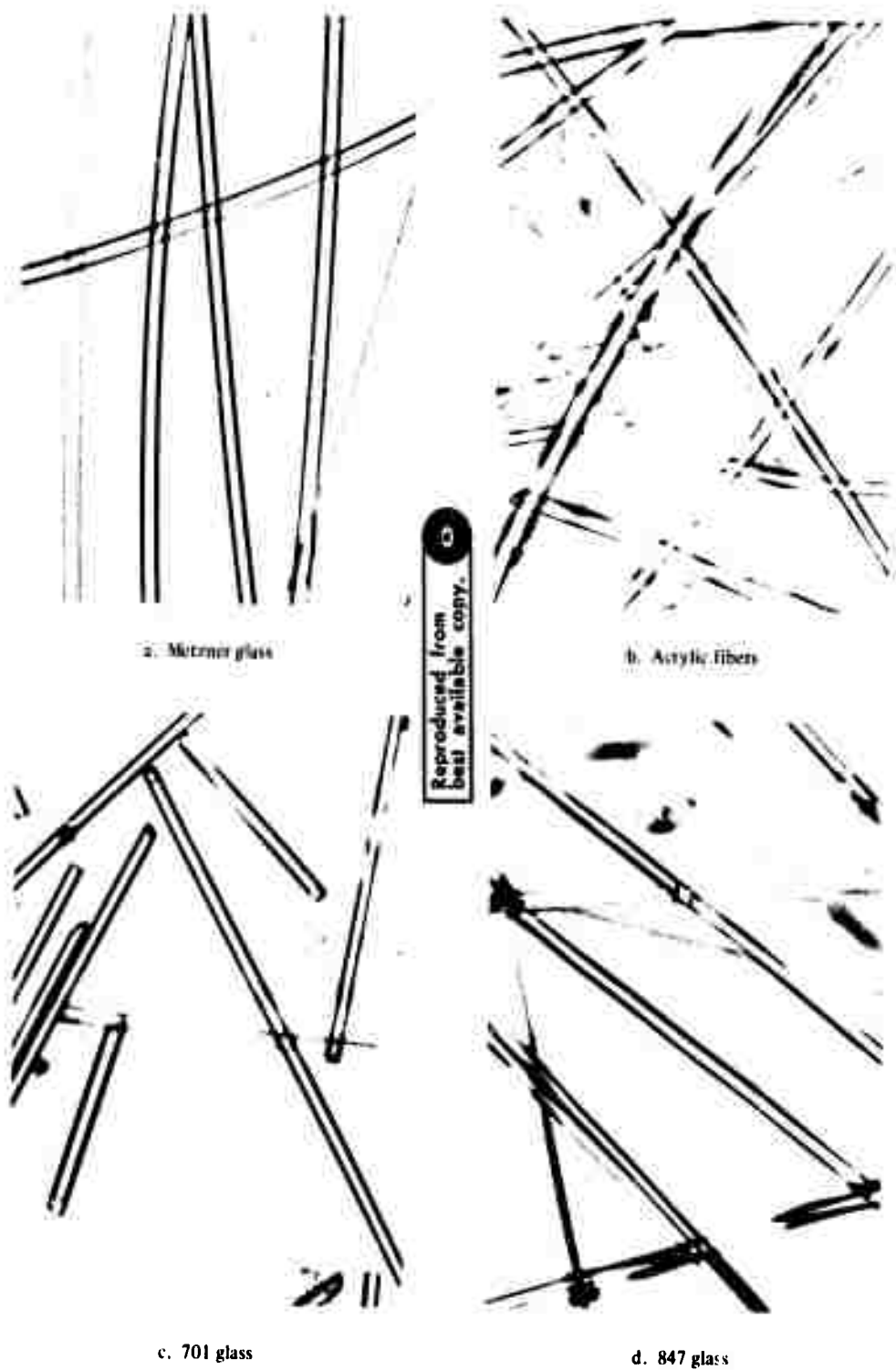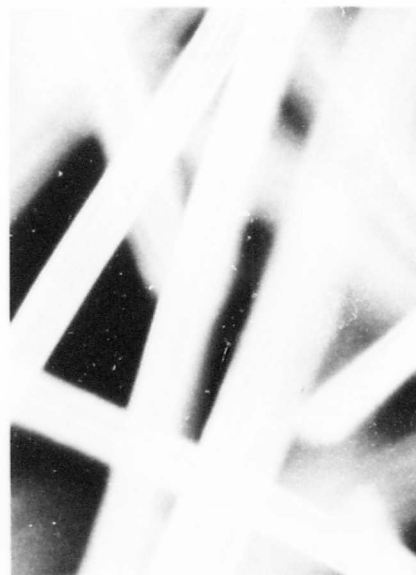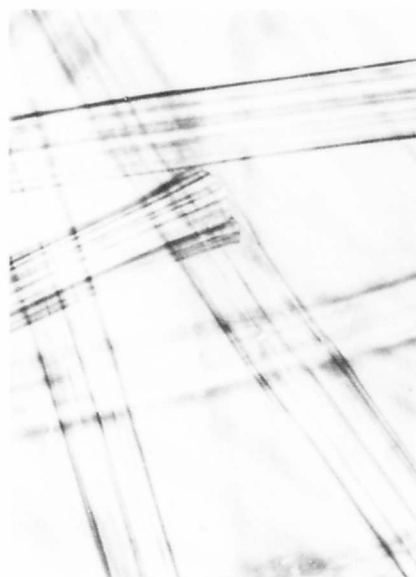
a. Metzner glass

b. Acrylic fibers

c. 701 glass

d. 847 glass

Figure 12. Photomicrographs at 304X of various drag-reducing fibers.

e. Solka-Floc

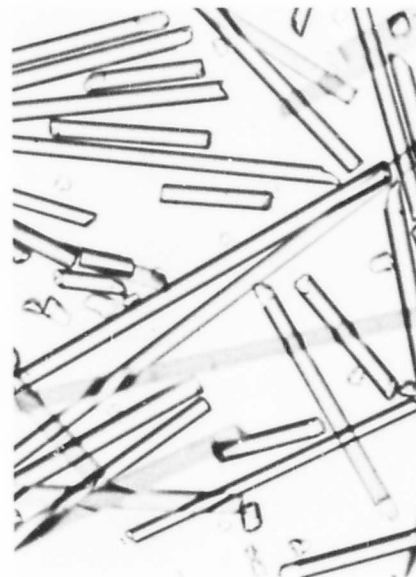f. 0.30 × 3 denier rayon
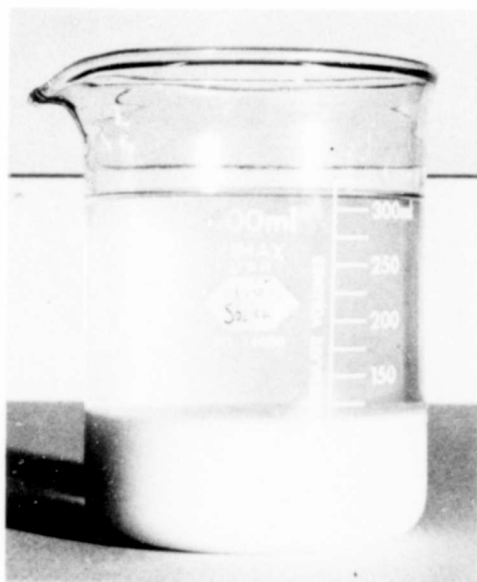
g. 0.45 × 5 denier rayon

h. Chopped glass fibers

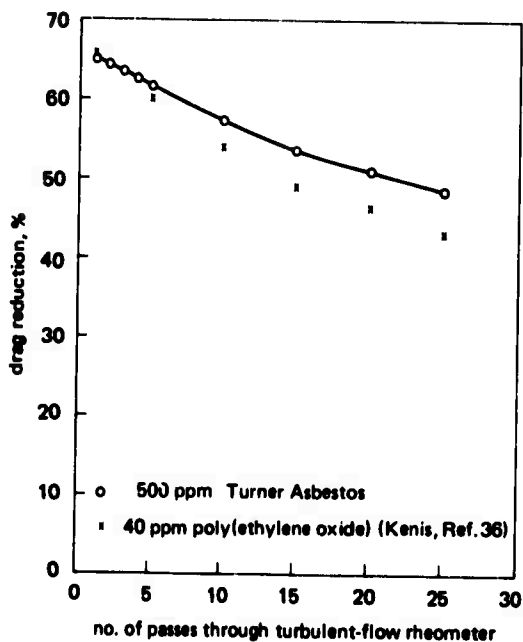Figure 12. Photomicrographs at 304X of various drag-reducing fibers (contd).

a. 1.6% Solka-Floc

b. 1.8% chopped glass fibers

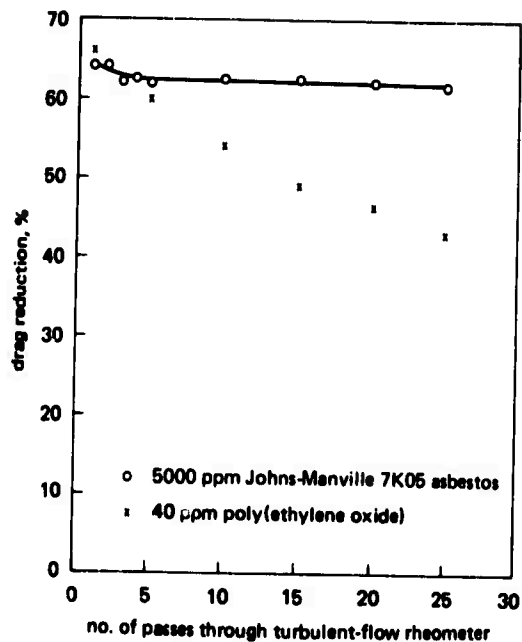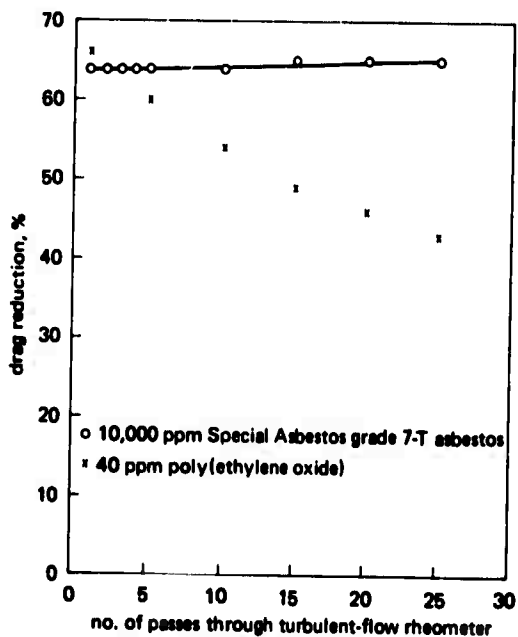c. 22% chopped glass

Figure 13. Photographs of settled fractions of experimental suspensions.

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Figure 14. Degradation test results for asbestos suspensions.

means of the Metzner and Reed generalized Reynolds number concept. The data for the clay suspension are included here for background interest only, in that no fiber-type drag reduction is believed present.

DEGRADATION EFFECTS

One of the principal problems in using polymer solutions in drag-reducing applications in which it is necessary to reuse or recirculate the drag-reducing solution many times is that the polymer becomes degraded, i.e., the polymer is broken due to shear stresses, so that the effective molecular weight becomes much lower and the friction-reducing effect tends to disappear. The more robust physical characteristics of fiber suspensions tends to give the impression that these materials would be much less affected by mechanical degradation. Figure 14 shows the results of degradation tests on three samples of asbestos fibers. Figure 14a shows that the most effective asbestos, the Turner asbestos, is indeed broken or aggregated into less effective masses by the shear stresses caused by multiple passes through the turbulent-flow rheometer. However, it is more resistant to degradation than the 40-ppm poly (ethylene oxide) polymer tested by Kenis (Ref. 36). Figures 14b and 14c, however, show that the asbestos fibers with lesser drag-reduction effectiveness are extremely resistant to degradation. In fact, the Special Asbestos fibers improve slightly in drag reduction with multiple passes through the rheometer.

CONCLUSIONS

The study of friction-reducing properties of asbestos and other fiber suspensions has indicated the following major conclusions:

1. In suspension, many types of fibers reduce turbulent friction.

2. Long, hair-like fibers provide the best friction reduction.

3. A greater length-to-diameter ratio improves the drag-reduction effectiveness.

4. Many fibers are resistant to mechanical degradation and thus can be used in recirculating or closed-system applications.

5. The drag-reduction effect is present in organic fluids as well as water.

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